Transparent Wireless Transmission over the ACCORDANCE Optical/Wireless Segment

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***Abstract*—Following the evaluation of FP7 proposals under the Call 4 objective, the network of the future, the STREP project ACCORDANCE has been funded to develop a converged copper/optical/radio OFDMA-based access network with high capacity and flexibility. The ACCORDANCE topology supports the integration of technologies and the interoperability of protocols in the form of distinctive network segments, e.g. legacy xPONs, xDSL, legacy wireless etc., through the application of OFDM(A) to provide segment access to and from the network central office. In particular, ACCORDANCE introduces the integration of dominant wired and wireless technologies in a hybrid network segment for greater flexibility and mobility at ease of last-mile implementation. To that extent, a converged passive optical network architecture supporting standard WiMAX/LTE signal formats by means of FDM subcarrier transmission downstream to remote ONU/BSs has been in the focus of this paper. Transparent operation for five FDM subcarriers carrying 3.5 GHz WiMAX channels has been demonstrated with measured EVMs of -31 dB obtained at selected ONU/BS antenna inputs for all subcarriers spacing. In addition, external versus direct modulation evaluation measurements exhibited superior SFDR figures for the former compared to the latter allowing for increased number of subcarriers in a FDM window and consequently network scalability.**

I. INTRODUCTION

The demand for modernizing available applications to typical residential and business customers in addition to the new breed of service on-the-go customers requires dramatically higher bandwidth network solutions offering media-rich applications such as high definition television (HDTV), video-on-demand (VoD), voice-over-IP (VoIP) and high speed internet [1].

To that extent, the network requirements to meet these challenges have not been fully explored and will potentially require major contributions from the photonics research community [1]. The research in photonic technology focuses on the development of networks and techniques to enable delivery of these services with Gigabits/s transmission pipes. In particular, passive optical networks (PONs) based primarily on time division multiplexing (TDM), have evolved as an access solution to provide simplicity and low operational cost with multiple of tens of Mbps provision to each user [2]. Wavelength division multiplexed PONs (WDM-PONs) have also been increasingly considered to deliver ultra high-speed services in the critical first mile by enabling service providers to offer dedicated wavelengths straight to homes and businesses over the existing optical backbone [2].

Furthermore, orthogonal frequency division multiplexing (OFDM(A)) has also been making its way into the optics world. Solutions for the optical core network which employ OFDM for achieving variable transmission rates ranging from 40 to 400Gbps by dynamically modifying the number of sub-carriers have been proposed [3], while with relevance to access networks a few studies have recently been presented which prove that OFDM can provide high capacity, long-reach and cost-effective operation for PONs [4].

Significantly, as the escalating demand in bandwidth provision at close subscriber proximity could be widely met by optical networking solutions, next generation access networks should also provide end users with great flexibility and mobility at ease of last-mile implementation [5]. Therefore, the convergence of fixed and mobile networks, such as WiMAX and LTE, is likely to deliver all desired benefits of data-centric, quality-service, mobile networks and should be carefully examined and studied. This imposes the fundamental challenge of the future access/metro network where transparent integration of wireless and optical servicing at the simultaneous introduction of dynamic multi-wavelength transmission need to be achieved.

This paper discusses all the above issues by introducing a novel access network architecture based on OFDM technology. As will be explained in detail, such an architecture is not only intended to offer much improved performance compared to existing or upcoming PON solutions [2], in terms of bandwidth allocation flexibility, component complexity, cost, number of users and network reach, but also inherently provide the opportunity for convergence between optical and radio access. In particular, this paper puts emphasis on the wireless-optical integration aspects of the proposed architecture where transparent transmission of micro-wave WiMAX channels from the optical line terminal (OLT) to optical network unit/base stations (ONU/BSs), by frequency division multiplexing (FDM), is investigated with respect to the error vector magnitude (EVM) and spurious free dynamic range (SFDR) of the non-linear optical network infrastructure.

II. OVERALL ACCORDANCE ARCHITECTURE

The proposed ACCORDANCE architecture is provided in Fig. 1. The topology consists of one OLT located at the Central Office (CO) and several ONUs located either at the user premises or at wireless base stations that will be used for providing connectivity to mobile terminals. One

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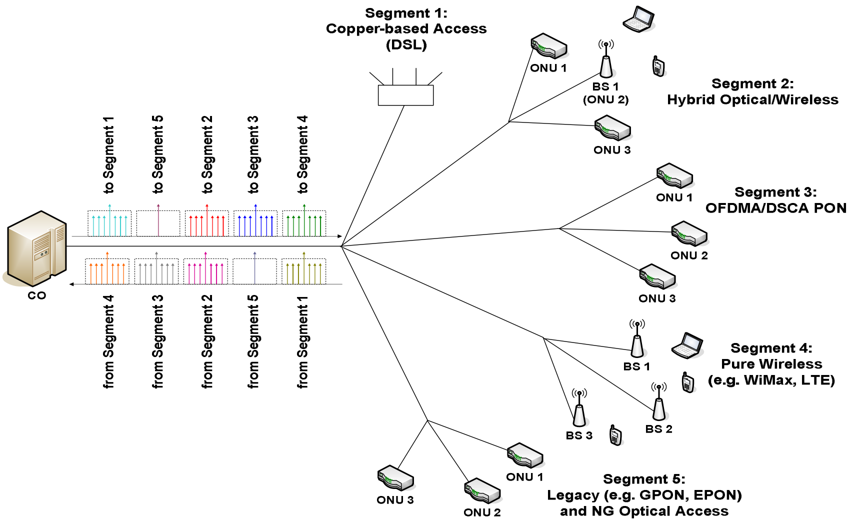

Figure 1. ACCORDANCE architecture

single feeder optical fiber from the OLT is used to carry all upstream and downstream signals up to a passive splitter which broadcasts them to multiple network segments. Then, further passive splitters, utilised for fiber-to-the-home (FTTH) deployments, are used for broadcasting the signals to all ONUs of each segment. Alternatively, some of those fibers can directly lead to wireless antennas, or switches with DSL interfaces. The OLT manages the assignment of traffic to a large number of sub-carriers which travel all along the optical distribution network (ODN), to be demultiplexed only at the user side and vice versa. The sub-carriers are grouped to form FDM channels with several tens or even hundreds of sub-carriers contained within one channel, each of them used for carrying traffic possibly by different providers and employing different technologies, such as GPON or EPON via RF-to-digital converters, but also wireless or copper-based ones.

The use of OFDM technology in the optical domain also offers the opportunity to facilitate the integration between wireless and wired networks. As the two transmission systems will use the same modulation format, it is possible to allocate different bands inside the frequency spectrum for different applications.

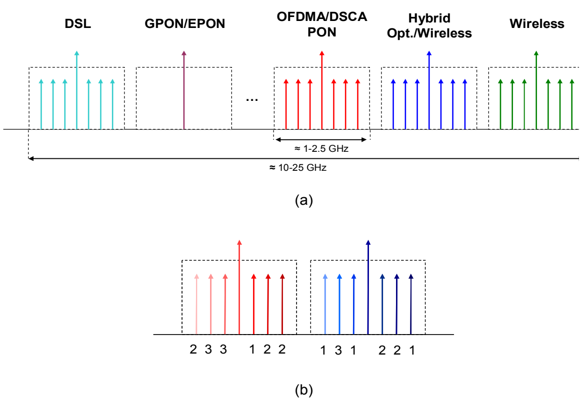

Figure 2. a) downstream FDM window assignment; b) assignment of individual sub-carriers to different ONUs

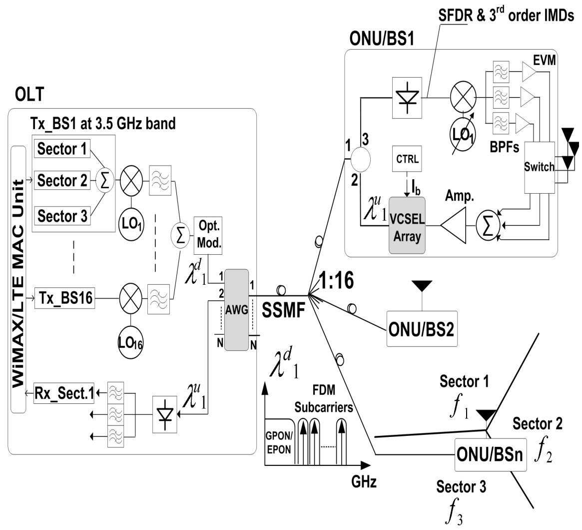

Figure 3. Proposed hybrid optical/wireless segment of the ACCORDANCE

Finally and as mentioned before, OFDM will enable convergence of the different access and radio services, namely FTTH, wireless and DSL technologies. Therefore, the CO can generally be thought of as a PON OLT but combining the additional functionalities of a DSLAM or a wireless base transceiver station (BTS) for WiMAX or LTE. It employs FDM to address different access network segments with an example described in Fig 2. The OFDMA/dynamic subcarrier allocation (DSCA) segment represents pure OFDM where subcarriers are allocated to users dynamically depending on bandwidth demand.

A. Hybrid Optical/Wireless Segment

A comprehensive diagram of a potential wireless-PON network segment solution, incorporating the developed modelling setup, is shown in Fig. 3. At this stage it should be clarified that this is one of possible solutions expected to be investigated in the course of the project to provide the optical/wireless ACCORDANCE segment. In addition, fixed WiMAX signal formats were considered initially to demonstrate feasibility of the proposed converged network to transparently deliver signals to BTSs. Further investigations will be performed to evaluate transmission performances of other signal formats such as mobile WiMAX and LTE.

At the OLT the RF WiMAX channels are frequency shifted using a predetermined LO and BPFs for each ONU/BS prior to being combined and modulated onto an optical carrier. The RF frequencies above 2.5 GHz were used in order to avoid interference with baseband E/GPON. The resulting FDM window on an optical carrier is broadcasted over a passive splitter to all ONU/BSs.

At an ONU/BS a single LO is only needed operating on the same frequency for the specific ONU/BS to downshift the WiMAX channels. This approach would significantly simplify the BS design, compared to traditional base-band FDM [6]. Multiple BPFs are then used to select each channel prior to transmission over the air. The frequency spacing between the FDM subcarriers will vary depending on the optical modulation method used, the number of supported channels and maximum electrical/optical component bandwidths. In addition, as illustrated in Fig. 3, frequency reuse factor of three across a base station is assumed therefore three different frequency channels are required from the OLT.

Another significant feature of the proposed topology lays in the use of low-cost long-wavelength VCSEL arrays [7, 8] at ONU/BSs to demonstrate colorless terminations upstream with simple coupling optics avoiding optical beat interference at the OLT receivers. In contrast to RSOAs [9], VCSEL arrays do not require upstream wavelengths transmitted downstream. Although RSOAs could be possibly investigated [9], interference among multiple delayed versions of the upstream signal generated due to Rayleigh backscattering is known to potentially degrade network performance. With VCSEL array approach re-modulation of downstream carriers is not required therefore avoiding the necessity of upstream wavelengths transmitted downstream simultaneously [9] with data for upstream modulation. The upstream wavelength selection is managed from the OLT by means of a controller circuit (CTRL) in an ONU/BS. A dense array waveguide grating (DAWG) in the OLT is then required to route multiple upstream wavelengths to the desired receiver.

The proposed centralized control in the OLT, compared to distributed approach in traditional wireless deployments, would allow for the creation of micro-cells with much higher spectral efficiency providing opportunities to support extended wireless features.

III. NETWORK MODELING

A physical layer simulation test-bed was implemented using the industrial standard Virtual Photonics Inc. (VPI), enriched in functionalities in view of MATLAB programming, to build an integrated simulation platform for the transmission of frequency shifted WiMAX channels over a PON. To exhibit the network feasibility, and constitute the architecture as a viable solution for the ACCORDANCE infrastructure, transmission measurements are initially focused in downstream as intermodulation distortions (IMDs), resulting from the nonlinearities in the optical link, could degrade the performance of FDM subcarriers. Consequently, the application of direct and external laser modulation is considered providing for performance measure comparisons between simplicity and increased network performance of the two scenarios for the transparent transmission of WiMAX over PONs. In upstream, a virtual point-to-point link is established through the VCSEL arrays, not requiring therefore the application of FDM.

To that extent, five different WiMAX channels at 3.5 GHz, assuming frequency reuse of one for a base station, are generated in the OLT and frequency shifted to address five ONU/BSs. The spacing of the five FDM subcarriers is varied in order to measure IMDs at an ONU/BS. To avoid the interference with G/EPON spectrum the first subcarrier in the FDM window was set at 4 GHz.

The IEEE802.16d WiMAX channels, modeled in MATLAB, comprise of 64-QAM, 256-OFDM modulation with maximum data rate of 70 Mbits/s per channel and relative constellation error (RCE) of -38 dB [10]. The higher modeled transmitter RCE, less than minimum required by the standard, is obtained since small WiMAX power levels are used to drive the optical modulators therefore exhibiting smaller distortions from non-linear high power amplifiers.

The combined FDM subcarriers are then initially directly modulated with commercially available distributed feedback (DFB) laser at 1490 nm [11] and applied over DAWG producing the maximum output power of +3 dBm into the fiber [11]. In addition, for external modulation a Mach–Zehnder modulator (MZM) was used to modulate a DFB laser with FDM subcarriers applied at modulator's RF input. The DFBs output power was set to account for various optical component losses generating the maximum lunched power of +3 dBm into the fiber.

At each ONU/BS, the received optical signal is then detected by an avalanche photodetector (APD) followed by RF subcarrier down-conversion to result to the transmitted WiMAX channel. To account for 1:16 splitter losses, a 14 dB optical attenuator is used after the fiber.

Performance evaluation measures include EVMs estimation at the ONU/BS1 remote antenna input as well as spurious free dynamic range (SFDR) figures for various FDM subcarriers spacings. The 3rd order IMD products are generated by increasing either the modulation index of the DFB laser or the modulation power inside the MZM RF input for direct and external modulation respectively.

IV. WIMAX FDM SUBCARRIERS TRANSMISSION PERFORMANCE

B. DML

As shown in Fig. 4 (top), direct modulation of the five frequency shifted WiMAX channels, has produced EVM versus laser modulation index a figure higher than -31 dB, as required by the WiMAX standard for 64-QAM modulation [10], for considered subcarrier spacing of 50, 100 and 300 MHz. In particularly the -31 dB EVM has been achieve at modulation indexes in the range of 0.8-0.9 for all subcarrier spacing. Consequently, the obtained EVM figures demonstrate the network transparency to the 70 Mbits/s WiMAX channels transmitted to a remote base stations based on the proposed FDM approach.

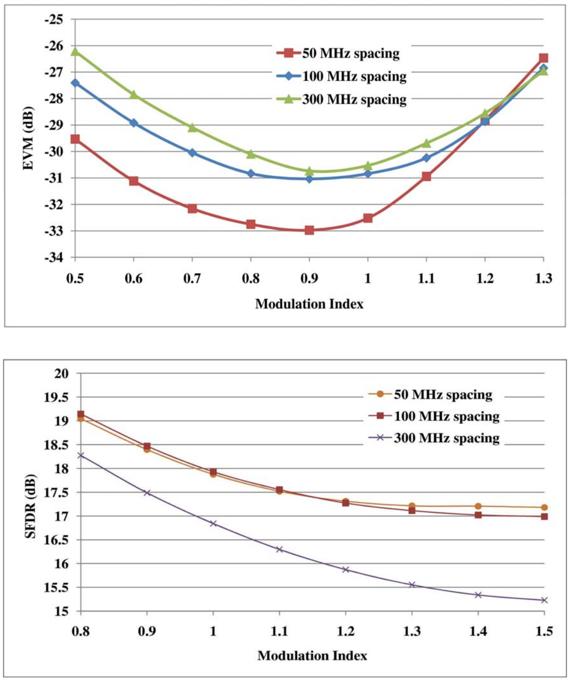

Figure 4. EVM (top) and SFDR (bottom) estimation for DML

In addition, the SFDR, with respect to the central FDM subcarrier, has displayed maximum dynamic range of 19 dB for 50 MHz and 100 MHz subcarriers spacing at 0.8 modulation index, as shown in Fig. 4 (bottom). As the channel spacing is increased, from 100 MHz to 300 MHz, the SFDR is reduced as expected due to the higher level of 3rd order IMD products that fall inside the desired channel. However, even with the highest considered channel spacing of 300 MHz, an EVM of -31 dB could still be achieved as shown in Fig. 4 (top). Since the DML in the proposed network could limit the maximum number of allowed FDM subcarriers, due to SFDR, an alternative chirpless option where a DFB laser is modulated by an external modulator could be applied as has been investigated in the following sub-section.

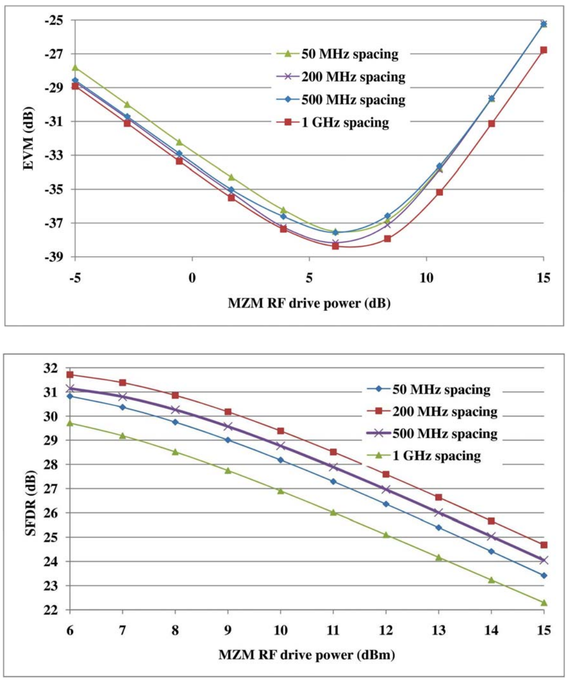

Figure 5. EVM (top) and SFDR (bottom) for MZM

C. MZM

As with the DML approach, in order to determine compliance with the WiMAX standard requirements at the ONU/BS1 antenna input, EVM characteristics as a function of the MZM RF drive power in the OLT was measured for four different subcarriers spacings. This time higher spacing of 50, 200, 500 MHz and 1GHz was considered, allowing for increased modulation bandwidths, as the MZM is expected to provide for higher dynamic range. To that extent, obtained EVM figures, as shown in Fig. 5 (top), have displayed EVMs greater than -38 dB for all subcarrier spacings at +6 dBm RF drive power to the MZM.

In addition, at +6 dBm RF drive power, the obtained SFDR figure, shown in Fig. 5 (bottom), of higher than 30 dB has been demonstrated compared to maximum of 19 dB with DML. This is expected since the MZM is biased at the quadrature point of the modulator's optical power versus voltage transfer function, cancelling all even-order distortion products [12]. As the RF drive power is increased, the power of IMD products becomes significant, reducing the network dynamic range. Significantly, the RF subcarriers from the OLT can occupy much wider bandwidth therefore enhancing the network scalability compared to DML. The MZM modulator in the OLT is typically shared by a large number of users minimizing the overall component cost.

V. CONCLUSIONS

This paper has presented the main features of the FP7 network architecture ACCORDANCE in support of convergence of passive optical infrastructures with standard network solutions, xDSL, E/GPON, wireless as well as the newly proposed OFDMA/DSCA PONs and optical/wireless PONs. Convergence is designed to be achieved based on the application of OFDM(A) providing wide variety of desirable characteristics, like increased aggregate bandwidth and scalability, enhanced resource allocation flexibility, longer reach and low CAPEX/OPEX, while also supporting multi-wavelength operation. Most importantly, all these can be achieved over typical splitter-PON infrastructures. In addition, it is envisaged to be fully compatible with the concept of next generation PONs since it facilitates interoperability and convergence with wireless networks. To that effect, this paper has presented a potential hybrid wireless/optical network segment to be utilized in the ACCORDANCE architecture featuring transparent WiMAX transmission by means of FDM over legacy xPONs. The optical network transparency to WiMAX channels has been demonstrated through the obtained EVM figures of higher than -31 dB for 64-QAM FDM WiMAX downstream channels with respect to various subcarrier spacings at both direct and external laser modulation. It has been shown that even at the maximum considered 1 GHz channel spacing, with external modulation, transparent WiMAX transmission could still be achieved compared to a maximum of 300 MHz spacing with DML. Also, a higher dynamic range of 30 dB has been measured in view of external modulation in relation to 19 dB obtained with DML allowing for increased modulation bandwidths.

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